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ELECTRODES FOR FUNCTIONAL ELECTRICAL STIMULATION

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SECTION B. DESIGN AND FABRICATION OF ELECTRODES, LEADS AND CONNECTORS

B.2.1.2: Polymer-Metal Foil-Polymer (PMP) Cuff Electrodes

The polymer-metal foil-polymer (PMP) electrode is a novel design that attempts to improve the mechanical reliability and ease the manufacturing process of spiral nerve cuff electrodes. The electrode design uses laser machining technology to fabricate an electrode pattern in a polymer-metal foil laminate. During this reporting period, we fabricated version three of the PMP electrode. The main problem we have focused on has been the deformation of the metal structure during Step 5 of the fabrication process. We have approached a solution to the deformation problem by evaluating alternative elastomers and lamination procedures. The deformation in the metal structure that occurred during lamination has been reduced to acceptable levels by placing a lower pressure on the structure during the lamination process.

Current Work

In the last reporting period, two PMP3 electrodes had begun manufacture. The second laser pass revealed some problems with the laser settings due to the change in elastomer from MED-4211 to MED-6015. A new batch of 10 PMP3 electrodes also began in order to begin *in vivo* testing with the PMP3 electrodes. The beginning steps of the fabrication process went smoothly and the laser settings were improved for the second laser pass. The improvement in the laser cuts using the new laser settings can be seen in the figure below.

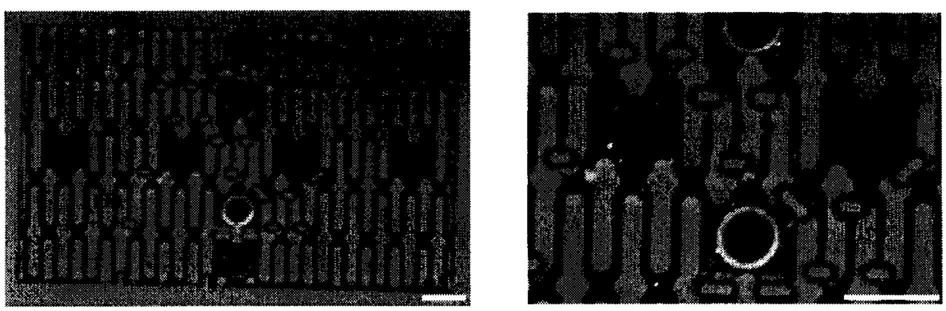

Figure B.1: The pictures above are of a PMP3 electrode after the second laser pass. These electrodes are made with MED-6015 elastomer. The laser cuts are clean and there are no tears in the silicone as in the previous two PMP3 electrodes. The scale bars represent 1 mm.

With the laser cutting improved, the first two PMP3 electrodes were continued through the fabrication process with the new set of 10 electrodes. Step5, cuff lamination, was attempted on the electrodes using the MED-6015 elastomer. Originally, the change to MED-6015 had been to help alleviate the possibility of the elastomer pushing out and deforming the platinum structure as it was pressed. Two electrodes were cuff laminated. These cuffs did distort and even broke within the platinum structure. Pictures of this distortion and the break in the platinum are in Figure B.2 below.

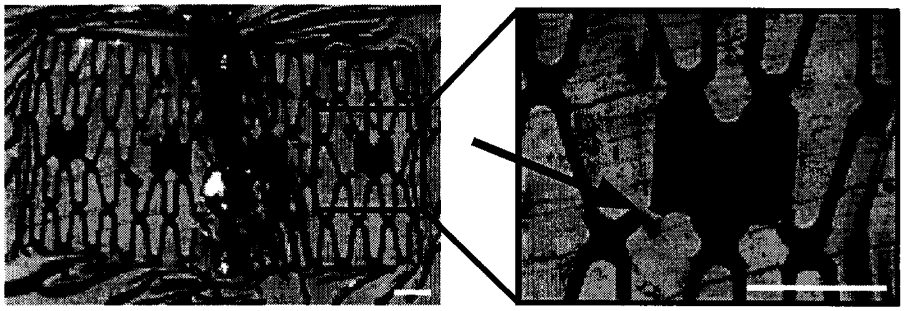

Figure B.2: The pictures above are of a PMP3 cuff electrode made with MED-6015. Wrinkling and distortion can be seen in both of the pictures above. The picture on the right shows a break (indicated by the arrow) in the platinum structure at a stimulation site. The scale bars represent 1 mm.

The similar break to the one seen in Figure B.2 was examined using Scanning Electron Microscopy. The silicone was partially removed at the site of the break.

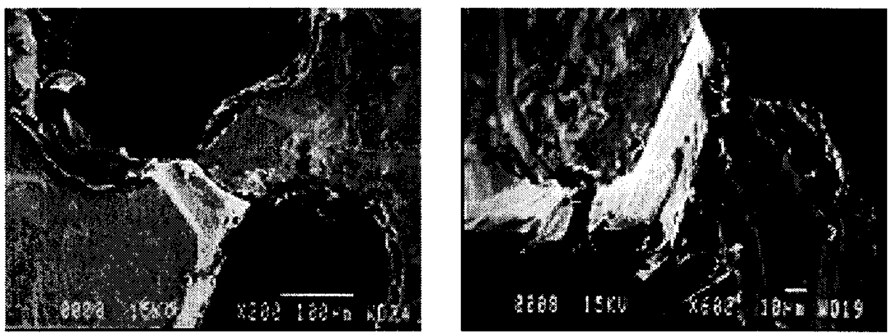

Figure B.3: This figure shows two pictures taken using the SEM. These pictures are of a break in the platinum of another PMP3 electrode made using MED-6015. The break occurred during cuff lamination, Step 5 of the fabrication process. The scale bars represent 100 micrometers in the first picture and 10 micrometers in the second.

It appears from the pictures that the break was a clean separation of the platinum. This would suggest that it was a break from tension during pressing.

This failure in the electrode was interpreted to mean that the deformation problem had not been totally solved by using the less viscous elastomer. In fact, the switch to the MED-6015 elastomer also brought additional concerns of excessive wrinkles in the cuff and poor curling properties. The properties of the elastomers used were revisited. All of the elastomers previously and currently used in PMP cuff fabrication were studied and compared. The comparison of the mechanical properties of these elastomers is shown in the table below.

Table B.1: Comparison of the Mechanical Properties of the Elastomers and Adhesives that have been used to produce PMP cuff electrodes

Property	MED-4210	MED-4211	MED-6015	MED2-4013
Viscosity, cps, A	90,000	100,000	5,000	80,000
Viscosity, cps, B	5,000	5,000	100	Thixotrpic
Durometer, shore A	30	29	50	15
Tensile Strength, psi	1000	750	1000	600
% Elongation	650	600	105	650
Tear Strength, ppi	100	45	no info	75

PMP fabrication started with the use of MED-4210 as the elastomer. This was chosen because it was the approved replica of a Dow Corning product formerly used. As production continued, NuSil, the company that makes the elastomer products, came out with an elastomer that they felt was an even better representation of the Dow Corning product, this was MED-4211. Therefore, we used MED-4211 until the point at which we experienced the deformation problems during manufacture. In an attempt to eliminate this problem, we switched to MED-6015 which has a much lower viscosity than the elastomers previously used. As described above, we continued to experience problems with deformation with this elastomer. Further research on elastomers yielded MED2-4013. This product is actually an adhesive. It is desired to use a product which has a high tensile strength and high percent elongation, but a lower viscosity than the MED-4211. MED2-4013 is a good compromise between the MED-4211 and the MED-6015. It is lower in viscosity, but still maintains a high tensile strength and percent elongation. Some other benefits to this product are that it does not need to be de-gased and, because it is an adhesive, it will adhere to the platinum. The adhesive will also seal the weld sites. Two electrodes were cuff laminated using the new MED2-4013 adhesive. Pictures of the platinum structure after lamination are shown in the figure below.

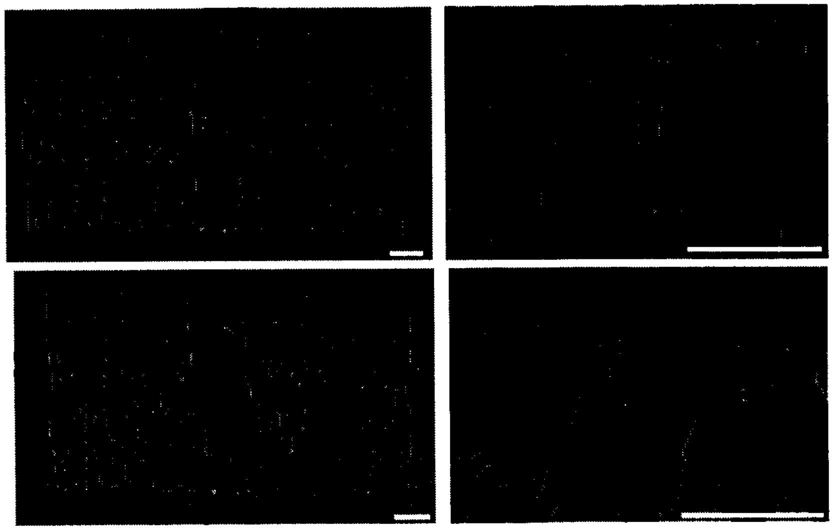

Figure B.4: The top two pictures are of a PMP3 3.0mm cuff made with MED2-4013. There were no wrinkles and there was very little deformation. The bottom two pictures are of a PMP3 2.8mm cuff electrode and were also made using MED2-4013. More deformation occurred, and the picture on the right shows a break on the top left corner of the stimulation site. The scale bars represent 1 mm.

The cuffs made using MED2-4013 had virtually no wrinkles and the deformation was significantly reduced. However, a break was still observed in the platinum. It was realized that the deformation may be caused by pressing the electrode too thin. An assumption was made that the metal shims used to determine the thickness of the electrode may be elastically deforming under the press. The thickness of the shims was measured using a micrometer, and then while being pressed using a feeler gage. The results showed that the shims were deforming approximately one mil during pressing. This means that we were pressing the electrode 1 mil thinner than the thickness of the components, thereby forcing it to deform and sometimes cause a break in the platinum. Cuff laminations were then performed using an extra one mil thickness of shims. The results of these laminations are shown in the pictures below.

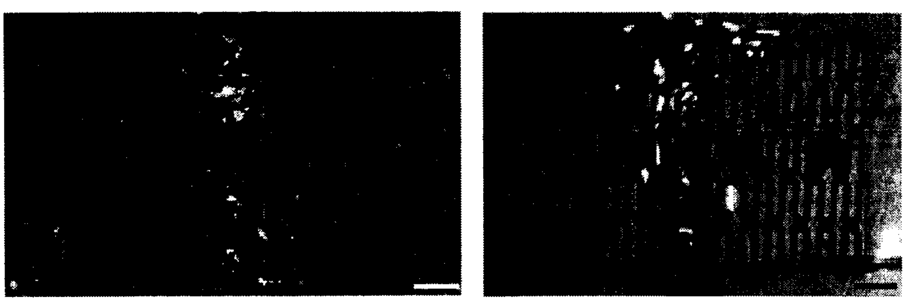

Figure B.5: These pictures are of a 3.0mm and a 2.8mm (L to R) cuff electrode made with MED2-4013 and with one extra mil of shim thickness. No deformation was observed. The scale bars represent 1 mm.

The PMP3 electrodes produced with the MED2-4013 and an additional one mil thickness have no deformation and exhibit the desired curling properties. In order to continue the contract requirements, another batch of 10 PMP3 electrodes have been manufactured for mechanical testing. These 10 electrodes have been furthered through all six steps of the manufacturing process with out any problems.

During this period, breaks in two of the PMP2 electrodes, which occurred after the manufacturing process was completed, were observed and evaluated. One of the breaks was found upon explant from *in vivo* testing. The other electrode with a break had been sterilized and prepared for implant, but upon finding the *in vivo* break, it along with the other electrodes were re-checked for conductivity. The location of the breaks is shown in the schematic below.

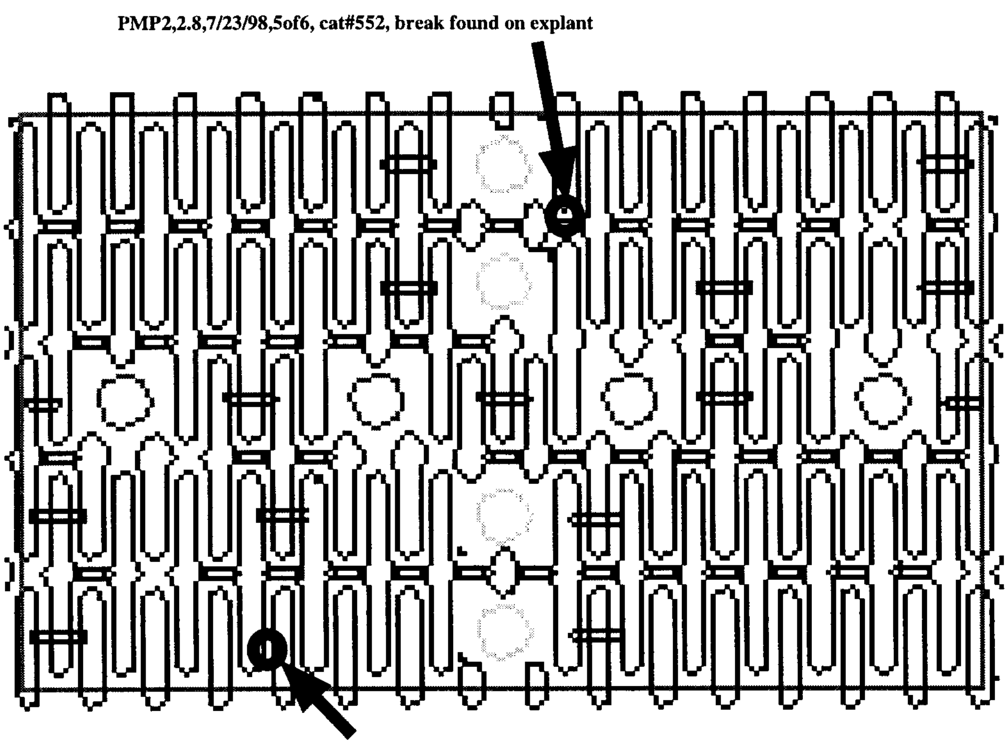

Figure B.6: Schematic of a PMP2 platinum structure with the locations of the breaks shown by the circles with arrows. These breaks happened in one electrode that was implanted, and one that was not.

The electrodes are tested for conductivity before cleaning, so the breaks are believed to have happened in cleaning, during the implant procedure, during implant, or during explant. The break in the electrode that was not implanted was looked at using scanning electron microscopy. The pictures from the microscopy seem to characterize the break as a break in tension. However, there is some beveling in the platinum, which may also describe fatigue. The section that was evaluated also had edges that were laser cut and one that was cut with a scalpel blade. The comparative pictures can be seen below.

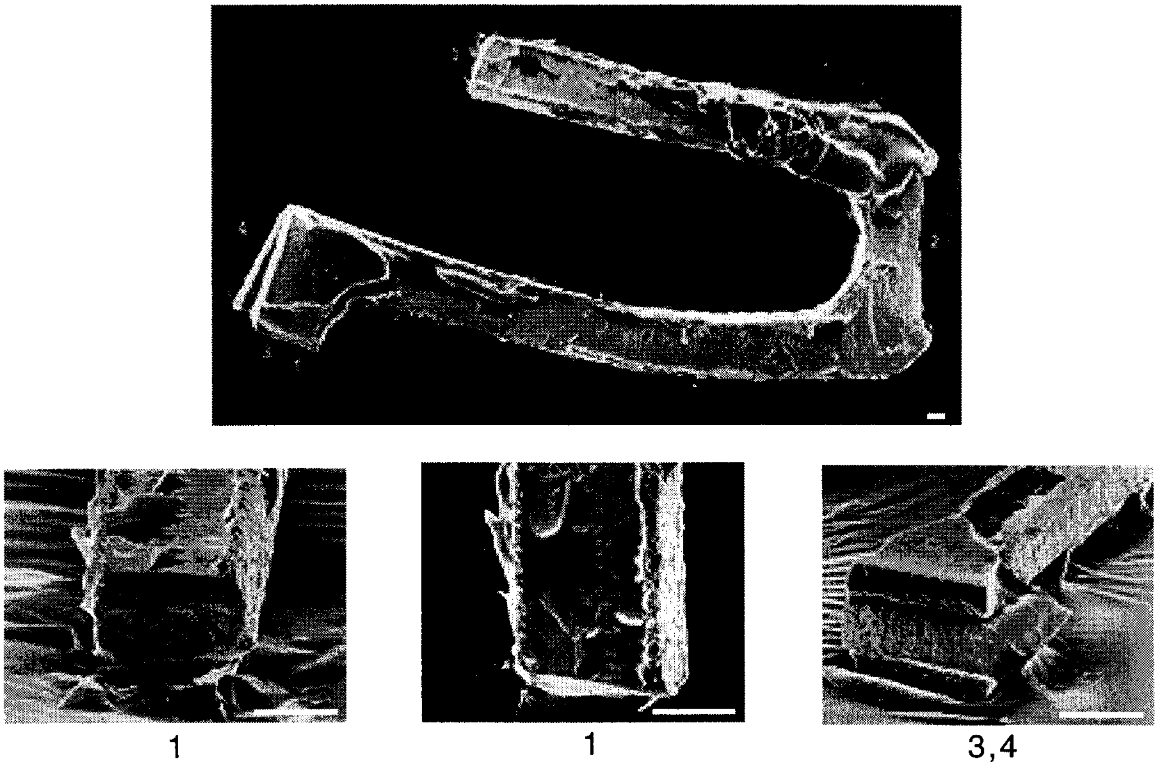

Figure B.7: The top picture is of the section of platinum that was removed from the electrode. The edges are labeled 1,2,3, and 4. Edge 1 is where the platinum broke, edges 2 and 4 were laser machined as part of the 2nd laser pass (step 3), and edge 3 was cut with a scalpel blade to excise the section. The three pictures below are numbered according to the edge they represent. The first two pictures show the broken edge. It is smooth, but a slight beveling can be seen in the picture taken from the top view. The last picture is of edges 3 and 4. The laser cut edge is smooth and the scalpel cut edge comes to a pointed edge. The scale bars in all four pictures represent 50 micrometers.

We plan to use these pictures help us to characterize the mode or failure and to look at other electrodes to determine if other failures have occurred that have gone undetected.

Future Work

New materials and methods of manufacture will continue to be evaluated in order to improve the PMP electrode. The PMP3 design will be studied experimentally and with computer modeling in order to optimize the design so that the platinum does not control the curl of the cuff. The break in the electrode that was implanted will be evaluated using electron microscopy. Any further failures or problems that arise during the completion of this contract will be analyzed and dealt with accordingly.

B.2.4.1: Silicone Rubber Sheeting

The goal of this project was to establish performance specifications for the silicone rubber sheeting used in the spiral cuff electrode fabrication. Tests were conducted to determine the mechanical and physical properties of four different silicone rubber sheeting formulations. Additionally, we investigated the effects of aging and sterilization on these properties.

Analysis of the data collected in Period #7 was performed during the present reporting period. The coefficient of friction data and additional tensile strength data are presented in this section.

The coefficient of friction of the samples was measured using an ASTM approved coefficient of friction fixture as described in PR #6. These measurements were taken using a crosshead speed of 200mm/min. The load cell was set on the lowest available setting, which yielded a ±1N error. This error is large for our application and its affect will be revealed in the standard deviations of the measurements. However, useful comparisons can still be made between the coefficients of friction for each formulation. The static coefficients of friction for the formulations tested are shown below for the control, aged, and sterilized groups. The coefficients of friction shown below are for dry silicone rubber on dry silicone rubber.

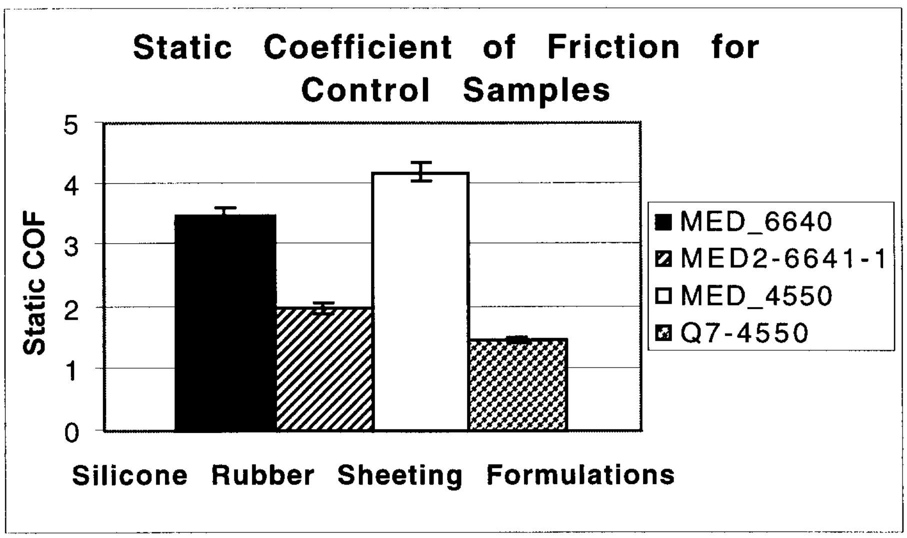

Figure B.8: The average coefficient of friction found for each silicone sheeting formulation tested is shown in the bar chart above. This chart consists of the results for the control groups.

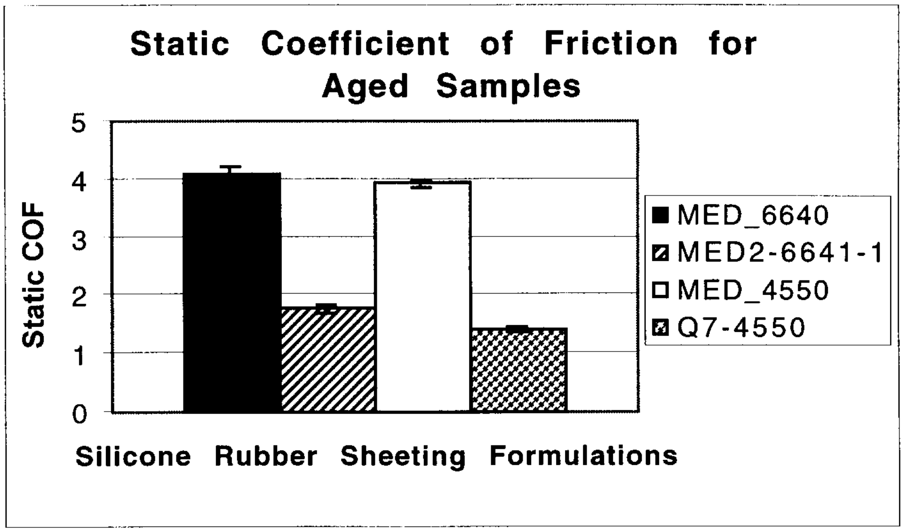

Figure B.9: The average coefficient of friction found for each silicone sheeting formulation tested is shown in the bar chart above. This chart consists of the results for the aged groups

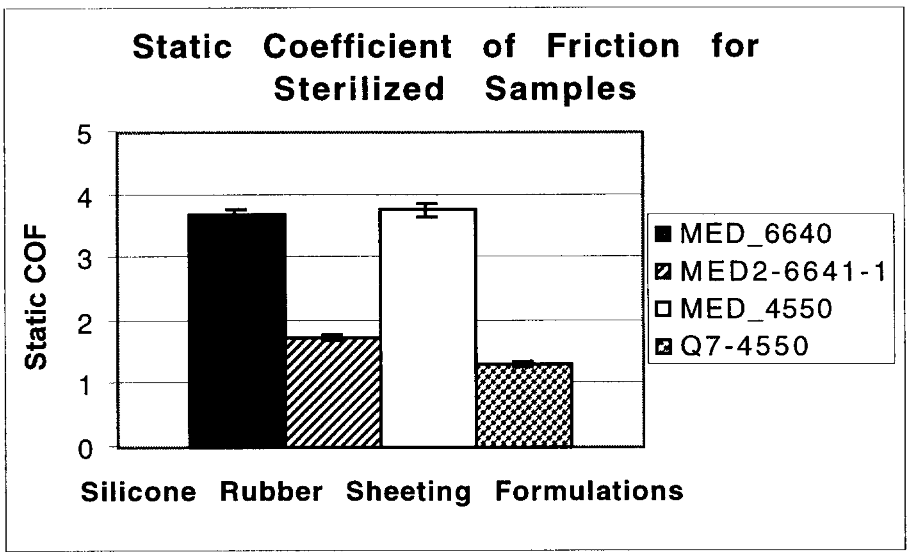

Figure B.10: The average coefficient of friction found for each silicone sheeting formulation tested is shown in the bar chart above. This chart consists of the results for the sterilized groups.

It can be seen that the Q7-4550 and MED2-6641-1 formulations consistently had the lowest coefficient of friction, while the MED2-6640 and MED-4550 consistently had the highest. Errors that may explain the deviation in the measurements above are the ±1N error in the load cell, wrinkles in both the samples and the base sheet, and the occurrences of stick-slip and plowing. "Plowing" occurs when two dissimilar materials roll or slide against one another. The harder material, as it slides across a softer material, will cause the softer material to bunch up in front of it. In our case, the heavier rubber sled pushed up the thinner silicone rubber and caused it to wrinkle. Most of these issues only play a factor in the deviation of the kinetic coefficient of friction, hence the low standard deviation for the static measurements.

The data from the tensile testing is presented in Figures B.11 through B.13.The stress-strain curves for the control samples of each formulation are plotted on the graph in Figure B.11. The standard deviation of the spring constant, k, is indicated on each curve by the surrounding gray region. In order to make certain that the stress vs. strain curve would be the same for different thickness' of silicone rubber sheeting, the MED-4550 was also tensile tested using three mil thick samples. The stress-strain curve for the three mil samples is also shown on the graph in Figure B.11. The two mil and three mil data should be the same since the data are in the form of normalized stress. It can be seen that the two and three mil MED-4550 sheeting tested are close, but are not equal. Their standard deviations do overlap, but only slightly. A larger sample size and the insurance of an equal testing environment would need to be provided before the two mil and three mil MED-4550 could be proven different.

After these data were analyzed, it was decided that it would be beneficial to find a relationship between the amount of stretch, thereby strain, necessary to produce a cuff of a particular diameter. The hypothesized outcome of this would be that there was an ultimate stress needed to produce a particular diameter. This information could then be correlated to the amount of strain needed from a particular silicone rubber sheeting formulation. Once this strain is known, then the cuff could be manufactured. This eliminates the trial and error process when a material change is made. In order to find this relationship, cuffs were manufactured using MED-4550, MED-6640, and MED2-6641-1 two mil stretch sheets. Each cuff made used a two mil stretched sheet and a two mil unstretched sheet of the same formulation. A six mil insert, made of two unstretched sheets of MED-4550 and MED-4211 elastomer in between, was used to mimic the platinum. The elastomer used for the cuff was MED2-4013 adhesive. The insert and the adhesive were kept constant for each formulation used. The results of these experiments are shown in Figure B.12. Figure B.13 was created using the data from Figures B.11 to convert the strain in Figure B.12 into the equivalent stress for each material.

Silicone Rubber Sheeting: Average Tensile Strength Curves for two mil Sheeting

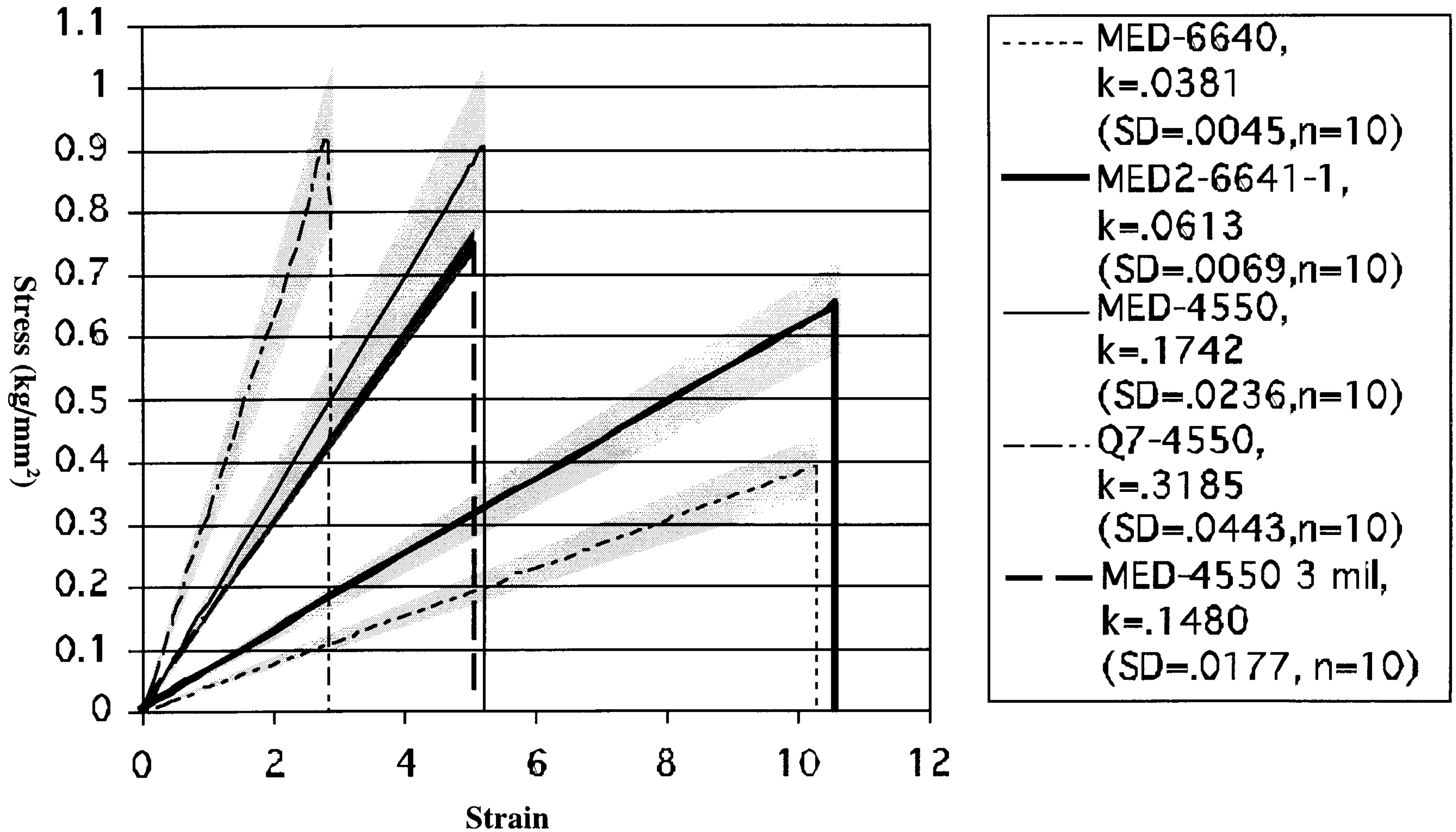

Figure B.11: The graph above shows the tensile strength curves for the four different silicone rubber sheeting formulations tested. These curves were obtained by tensile testing to failure ten samples per formulation. The "k" value shown in the legend is the slope of the curve. This is also the spring constant for the material. The standard deviation (SD) is shown for the spring constant.

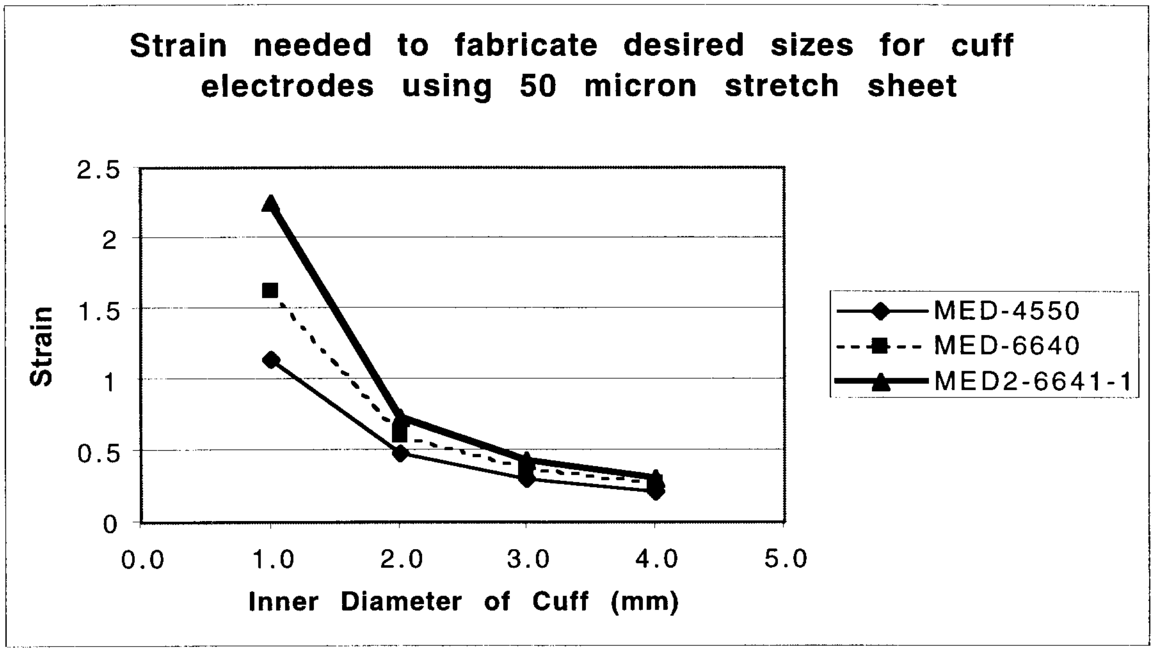

Figure B.12: This graph shows the amount of strain required by the system that the stretched layer of silicone must produce. This data was obtained by fabricating cuffs using various lengths of stretch.

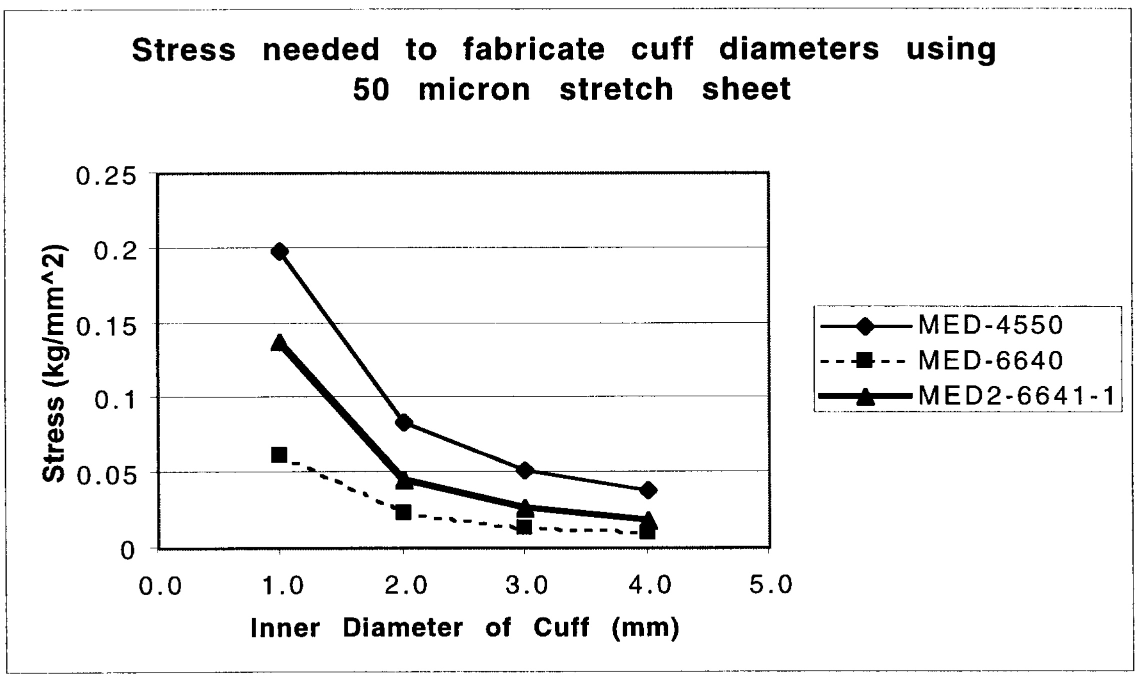

Figure B.13: This graph depicts the amount of stress required to Fabricate cuffs of various sizes. This data was obtained by using the spring constant information from Figure B.11 and applying it to the strain data in Figure B.12.

It appears from Figure B.13 that there is not an ultimate stress that yields a particular diameter among all formulations. This may be because the two mil unstretched sheet was not the same formulation for the fabrication of the different cuffs to determine the strain versus diameter curve. A new set of cuffs will be produced using a two mil MED-4550 sheet as the bottom sheet for each cuff. The results of this test will be given in PR#9.

Future Work

A set of cuffs will be produced using the same procedure as above, but with the bottom, unstretched sheet MED-4550 for all of the cuffs made. The stress-strain relationship for each formulation will be determined and discussed in the next period. The silicone rubber sheeting will continue to be tested in order to characterize the behavior of the sheeting when stretched and bonded to other material formulations. Specifications for the formulation, or combination of formulations that should be used in cuff manufacture will be given upon testing completion.

B.2.6 *In Vivo* Testing

The *in vivo* testing to be performed in this contract consists of three PMP electrodes implanted in cats for 3 months each. Two PMP2 electrodes were implanted. These electrodes were explanted between one and two months after implant due to suspected electrode failures. These implants are described in Section C.I.2.2 of this report and briefly described in Section B.2.1.2. Since the explants and analysis, three PMP3 electrodes made with MED2-4013 adhesive and with one mil extra of shim space, have been implanted. Preliminary stimulation testing on these electrodes has been successful. The PMP3 electrodes have been in for over a month and there have been no suspected electrode failures. More information on the stimulation results can be found in Section C.I.2.2 of this report.

Future Work

One of the PMP2 electrodes explanted had a break in the platinum. This break will be evaluated using scanning electron microscopy in order to characterize the mode of failure. The three implanted PMP3 electrodes will continue to be stimulated over the next two months. At the end of that period the electrodes will be explanted and tested according to the contract.

SECTION C. IN VIVO EVALUATION OF ELECTRODES

C.I.2.2: Selective Activation Stability Over Range and Time; Chronic Animal Tests

Abstract

The objective of this project is to qualify nerve cuff electrodes for use in human subjects. We have two designs that we believe are technologically feasible and reliable, the PMP design and the wiggle-wire design. The first design, the PMP electrode, contains a sheet of platinum that is cut with a laser and embedded into the silicone rubber to produce a thin, multi-contact nerve cuff electrode. The wiggle-wire electrode is produced with the lead wires being bent back and forth in the plane of the electrode to allow the conductor to accommodate compression and tension during flexion of the cuff.

Chronic experiments, designed to provide both histological data on the safety of these electrode designs and stimulation results on the long-term stability of the recruitment properties of the electrodes, were begun in period #7. The stability of the electrode was previously tested by Grill [1996] based on the change in the threshold value over time but the stability of more complicated electrode configurations was not tested. During the course of these chronic experiments, we will test field steering techniques to verify that their properties stabilize over time.

Progress

A total of nine implants have been performed. Five implantation procedures were reported in the previous progress report, and the remaining four were implanted during the present reporting period. Of the five previously reported implants, one animal did not survive the surgery and a second animal developed a serious skin condition that lead to the animal being euthanized at seven weeks. Not including the animal that didn't survive surgery, three animals were implanted with a wiggle-wire type of electrode, two animals were implanted PMP2 electrodes, and the remaining three animals were implanted with PMP3 electrodes. Each animal was monitored for any unusual pain, loss of function or loss of reflex. No significant change in animal behavior, reflexes or strength was found in any of the animals. Testing of the torque responses due to stimulation applied to the nerve cuff electrode began approximately three weeks post-implant. A three-week time was decided based on previous studies, which indicate that full encapsulation and stabilization of the nerve cuff electrode takes place over the first three weeks.

Both of the animals implanted with the earlier version of the PMP electrode (PMP2), were found to have electrode related problems. In one case, only the 270° contact produced an output. In the second case, the 0° contact did not produce any output. The remaining three contacts in this second case all appeared to produce the same output. Suspected breakage and/or cuff placement problems resulted in both of these animals being terminated at 43 and 30 days respectively. Each animal was perfused with a combination of paraformaldehyde and glutaraldehyde. The area around the sciatic nerve was carefully dissected away and each of the individual branches were identified and marked. The sciatic nerve and surrounding tissue was excised along with the lead wire and its corresponding surrounding tissue. The excised tissue was then soaked in the glutaraldehyde solution for two days and then transferred to a sodium cacodylate buffer solution. Careful dissection of the tissue around the sciatic nerve was performed to see the orientation and location of the nerve cuff relative to the nerve trunk. In both cases the cuff electrodes were found to be wrapped around the nerves and contained within a thin encapsulation pocket. In neither case did the electrode position or the tissue growth give any indications of the cause of the stimulation complications. The orientation of the electrode relative to the nerve trunk was marked on the nerve by sutures tied to the epineurial sheath both proximal and distal to the cuff location. The nerve cuff was then removed from the nerve trunk so that cross sections of the nerve at the location of the electrode could be taken. Continuity of each lead and contact was tested for each electrode. Only one discontinuity was found. Under closer examination, the discontinuity was found to occur in the platinum structure near the weld pad, at a similar location to the previously noted failures as described in Section B. Figure C.1 shows a view of the electrode found to have a break in its path. The inset in Figure C.1 is a magnified view of the electrode where the breakage was found. Shown in the inset is how the platinum trace on either side of the break displaces when slight pressure is applied with a pair of forceps. Due to image quality, dashed lines were added to highlight the edges of the platinum.

Data collection from each animal was begun during the present reporting period and will continue through the next reporting period. Multiple sessions will be collected from each animal to investigate the level of repeatability that is possible from the implanted electrodes. At the conclusion of the next reporting period, we anticipate the data collection to be completed and the harvesting of the tissue and nerve sample to have begun. The nerve sections will be used to correlate the location of each electrode contact with its respective stimulation results. Any neurological anomalies found within the nerve trunk will also be noted.

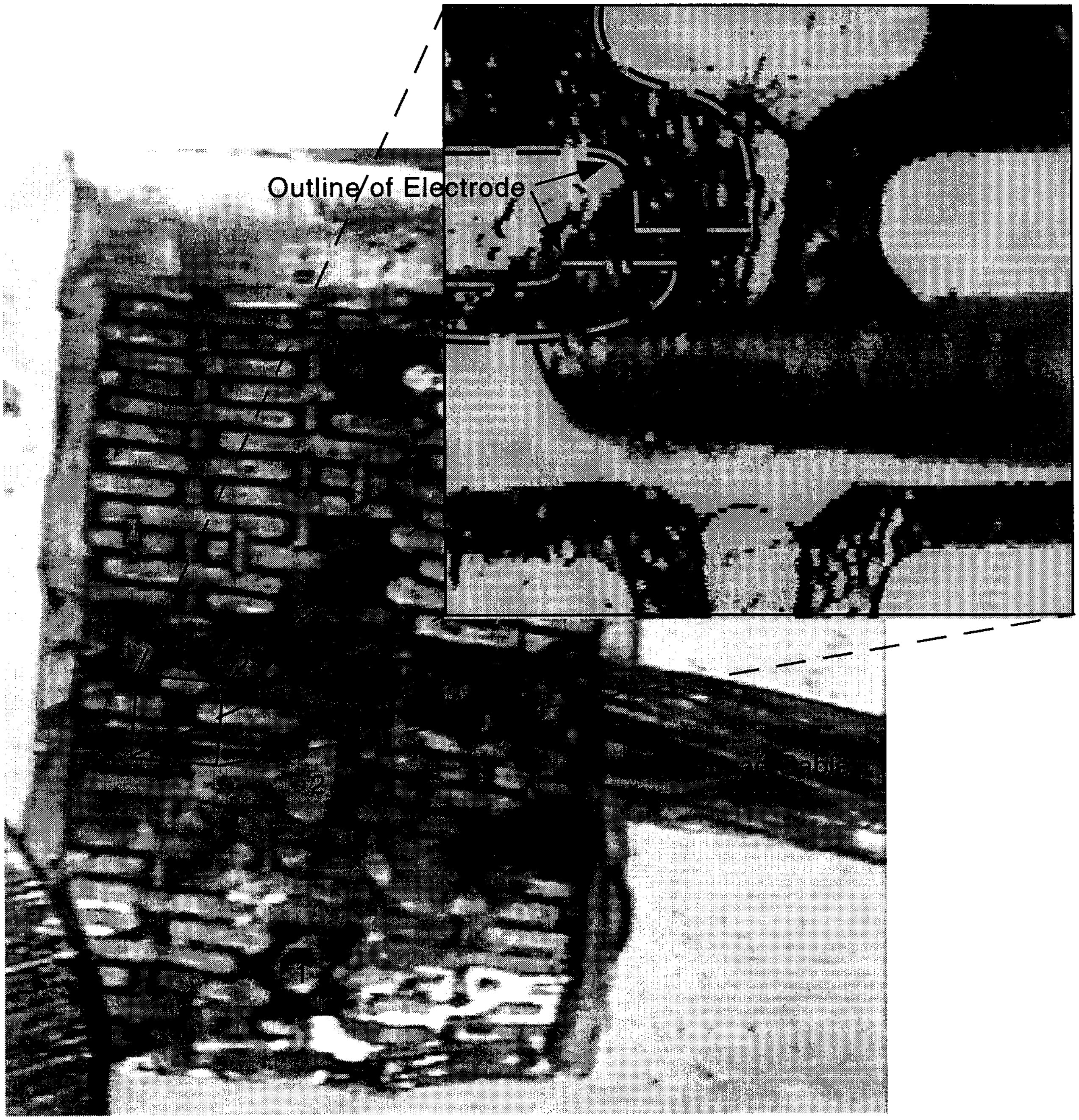

Figure C.1: After explant the electrode was inspected for any breaks in the lead wires or platinum structure. A break in the platinum path serving the #1 contact was found. A magnified view of the break is shown in the inset. A pair of forceps was used to apply a small pressure to the platinum path on one side of the break. A separation of the two sides of the path was observed. Dashed lines are used to enhance the location of the platinum edges.